SAR Remote Sensing of Nonlinear Internal Waves in the South China Sea

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LONG-TERM GOAL

To understand the environmental effects (e.g. bottom topography, shoaling, mixing, and current/shear) on nonlinear internal wave generation, evolution, and dissipation in the South China Sea by using satellite synthetic aperture radar (SAR) imagery, in-situ data, and numerical models.

OBJECTIVES

The objective of this study is focused on observations and analysis of nonlinear internal waves and mesoscale features (e. g. eddies, fronts) in the shelf-break region of the South China Sea. The task is concentrated on the collection and analysis of SAR imagery (ERS-2, ENVISAT ASAR, and RADARSAT ScanSAR) and mooring data from field experiments in the South China Sea. Of particular interest is the generation of huge internal waves caused by the branch out of Kuroshio through Luzon Strait and its evolution and dissipation on the shelf break.

APPROACH

The approach is to use the SAR data in conjunction with the in-situ measurements from field experiments to calibrate and validate SAR imaging mechanism of nonlinear internal waves, and to integrate all data by wave model for data assimilation. A validated and calibrated algorithm and model can be very useful for the understanding of shelf processes and for the applications of internal wave effects on acoustic propagation. A parametric study for various environmental conditions will be carried out to demonstrate and assess the nonlinear effects such as bottom topography (across critical depth), shoaling, stratification, and dissipation. The generation and evolution of internal waves (elevation versus depression, and mode-one versus mode-two), and wave-wave interaction will be studied using satellite data in conjunction with in-situ data from the field experiments. Key collaborators of this project are Dr. Antony Liu at NASA Goddard Space Flight Center, currently detailed at ONR Global –Asia, and Prof. Ming-Kuang Hsu at Northern Taiwan Institute of Science and Technology, Taiwan.

WORK COMPLETED

During this report period, in collaboration with Dr. Antony Liu at ONRG-Asia and Prof. Ming-Kuang Hsu from Taiwan, several dozens of SAR images from ERS-2, ENVISAT ASAR, and RADARSAT ScanSAR during the South China Sea 2007 experiment (SCS'07) were processed and analyzed for nonlinear internal waves study in the South China Sea (SCS). Taking the advantage of the 28 minute

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acquisition time offset between ERS-2 and ENVISAT SAR and their almost exactly same path, the internal wave propagation and ocean surface drift can be observed and tracked through pairs of sequential SAR images respectively from these two satellites. A wavelet transform based internal wave tracking method for deriving internal wave propagation vectors from ENVISAT and ERS-2 SAR image was developed and used in case studies. An oral presentation, entitled "SAR data collection and analysis during SCS'07" and authored jointly with Dr. Liu and Prof. Hsu, was presented at ONR NLIWI PI Experiment Integration Meeting in Girdwood, Alaska on August 26-31, 2007.

RESULTS

During SCS'07, 84 scenes of ERS-2 images, 5 ENVISAT wide swath images, and 6 RADARSAT ScanSAR images were collected and processed. Based on these SAR images and the SAR image collected during SCS'05, the internal wave distribution map in the Luzon Strait during SCS'05 and SCS'07 was compiled. Figure 1 shows the distribution map where the red and green curves represent the internal waves captured by the SAR images during SCS'05 and SCS'07, respectively, while the black curves represent the internal waves revealed by ERS-1 SAR image on June 16, 1995. Based on the internal wave distribution map, most of the internal waves during the periods in the northeast part of South China Sea are propagating westward as they did in other periods previously reported by Liu and Hsu (2004). It is believed that Luzon Strait is the generation source of most of nonlinear internal waves in the South China Sea. However, Figure 1 indicates that there may be multiple generation sources in the Luzon Strait for internal waves in the SCS since the internal waves in the map points to different locations. The existence of locally generated internal waves in the Babuyan Channel off the northern coast of Luzon of Philippine revealed by the SAR images during both SCS'05 and SCS'07 as shown in the map provides the support for the multiple generation sources theory. Recent work by Liu and Hsu (2003) has suggested that the long-crested internal waves near Luzon Strait are produced by the connection along the crest of many individual wave packets generated from different sources or sills in the strait, the so-called "Hand-in-Hand" phenomenon from multiple sources (Hsu and Liu, 2003). The internal wave packet shown in the ERS-1 SAR image on June 16, 1995 (black curves in the map) appears to be the case. Therefore, uncovering all potential generation locations of internal waves in the Luzon Strait is important for testing this and other proposed generation theories. The detailed wave generation mechanisms and locations are still not well understood since there are not enough in-situ measurements and remote sensing data.

ERS-2 and ENVISAT have acquisition time offset around 28 minutes and almost the exactly same path. This enables us to observe and track the evolutions of ocean surface features that have about 28 minute and longer coherent time periods by using pairs of sequential SAR images obtained respectively from ERS-2 and ENVISAT. The challenges of this approach include co-registering the images and identifying the same features in the sequential satellite images that are obtained from sensors in different satellite.

Nonlinear internal waves have been frequently observed in the South China Sea around the Dong-Sha Islands both from field measurements and satellite observations (Liu et al., 1998; Hsu and Liu, 2000; Liu et al., 2004). Figure 2 (a) and (b) show a subscene (latitude: 20.30°N ~ 21.00°N; longitude: 116.50°E ~ 117.20°E) of ENVISAT and ERS-2 SAR images collected on April 16, 2003 at 2:14 UTC and 2:42 UTC, respectively, and Figure 2(c) shows a subscene of MODIS band-2 image at 3:10 UTC over the same area with the bright and dark gray value reversed to the same pattern in Figures 2(a) and 2(b). They clearly show a westerly propagating internal wave broke into three parts after it encountered the Dong-Sha reef. While its northern and southern parts, the parts of the wave in the north and south of Dong-Sha reef respectively, continued their westerly propagation, its middle section probably was reflected to the east of the reef after the wave encountered the reef and appeared as the bright wave feature in the east of the reef in the images. For further detailed analysis of wave refraction, Figure 3 (Left panel) shows the same subscene of ENVISAT image as that in Figure 2(a), but it is overlaid with the locations of internal waves digitized from ENVISAT (red), ERS-2 (magenta), and MODIS (blue) images shown in Figure 2. The figure shows wave refraction and reflection caused by the interactions of internal solitons with Dong-Sha Island and coral reef around it. After encountering Dong-Sha reef, the northern and southern parts of the internal wave continued to propagate westerly with changing directions and speeds, and the middle part of the internal wave was reflected to the east of the reef and propagated easterly. In both the northern and the southern parts of internal waves, the ends close to the reef propagate very slowly due to the reef bottom drag/friction, while the ends far from the reef propagate relatively faster. Thus, it seems they were rotating around the reef.

To derive the internal wave propagation vectors from the sequential ENVISAT and ERS-2 SAR images, the SAR images are first mapped to the same coordinate system with the same pixel size. Then, a two-dimensional Gaussian wavelet (often referred to as a "Mexican hat" wavelet) transform was applied to them to filter out the uninterested features. Wavelet transforms are analogous to Fourier transform but are localized both in frequency and time. A two-dimensional wavelet transform is a highly efficient band-pass data filter, which can be used to separate various scales of processes. This is critical for observing and tracking features using images from two different satellites since the use of two sensors from different satellites will have quite different dynamic data range, and the filtered data with the same dynamic range are essential for feature tracking. Then the filtered images were examined to find matching features using templates and the results were then converted to motion vectors.

As a case study, the ENVISAT and ERS-2 SAR images shown in Figure 2 were first co-registered by mapping both of them to the longitude x latitude coordinate system with same pixel sizes 0.0014° x 0.0014° (about 154m x 154 m). Then the feature tracking algorithm outlined above was used to derive the internal wave propagation vectors. The so derived internal wave propagation vectors were shown in the left panel of Figure 4 in blue with the ENVISAT image as the background image. The right panel shows there plots of the magnitudes of the internal wave propagation vectors corresponding to the northern, middle, and southern parts of the internal wave. The directions and magnitudes of the derived internal wave propagation vectors clearly show that the internal wave refraction occurs along the northern part of the wave and wave reflection in the middle of the internal wave.

As another case study, the ENVISAT and ERS-2 SAR images collected on May 6, 2005 with 28 minute acquisition time offset were used to derive the internal wave propagation vectors. Figure 5 (a) shows the overlay of these two images with ENVISAT SAR image as red component and ERS-2 as green component. It clearly shows the internal wave position and signature differences in 28 minutes. Figure 5 (b) shows the derived internal wave propagation vectors which mostly move toward northwest and are in agreement with Figure 5(a). The fifth vector from the top in the figure that moves toward southwest appears to be wrong and is due to the weak internal wave signatures in the area where it locates.

These case study results indicate that ENVISAT and ERS-2 SAR images separated by 28 minutes in time can be used to derive internal wave propagation vector, and can help to identify oceanic processes such as currents and eddies. However, further validation and calibration with in-situ measurements are definitely warranted for future study.

The two-dimensional Mexican hat wavelet has been applied to satellite images to separate processes at various scales, including relative phase/location information for coastal monitoring applications (Liu et al., 1997a), and for ice edge and ice floe tracking (Liu et al., 1997b). It can also been used for separating texture or features; for near real-time "quick look" analyses of satellite data for feature detection; and for data reduction using a binary image.

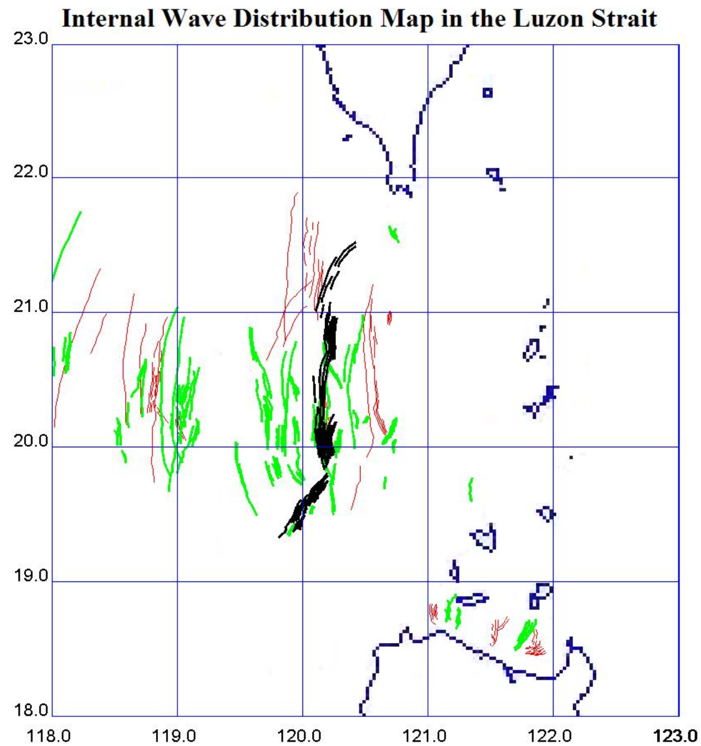

Figure 1. Internal wave distribution map in the Luzon Strait during SCS'05 (red)and SCS'07 (green) and on June 16, 1995 (black).

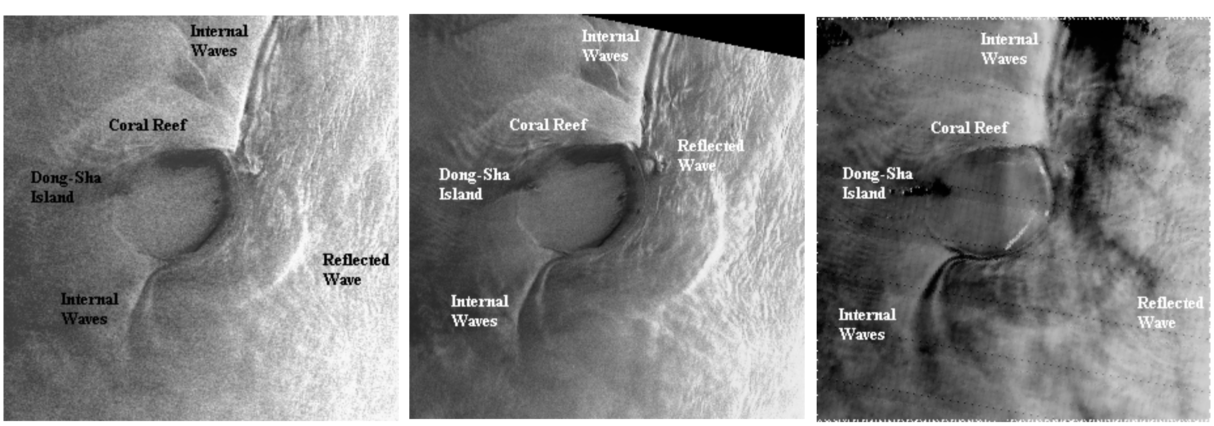

Figure 2. Subscenes of (a) ENVISAT ASAR, (b) ERS-2 SAR, and (c) MODIS band 2 image (from left to right) around Dong-Sha Island collected on April 16, 2003 at 2:14 UTC, 2:42 UTC, and 3:10 UTC, respectively.

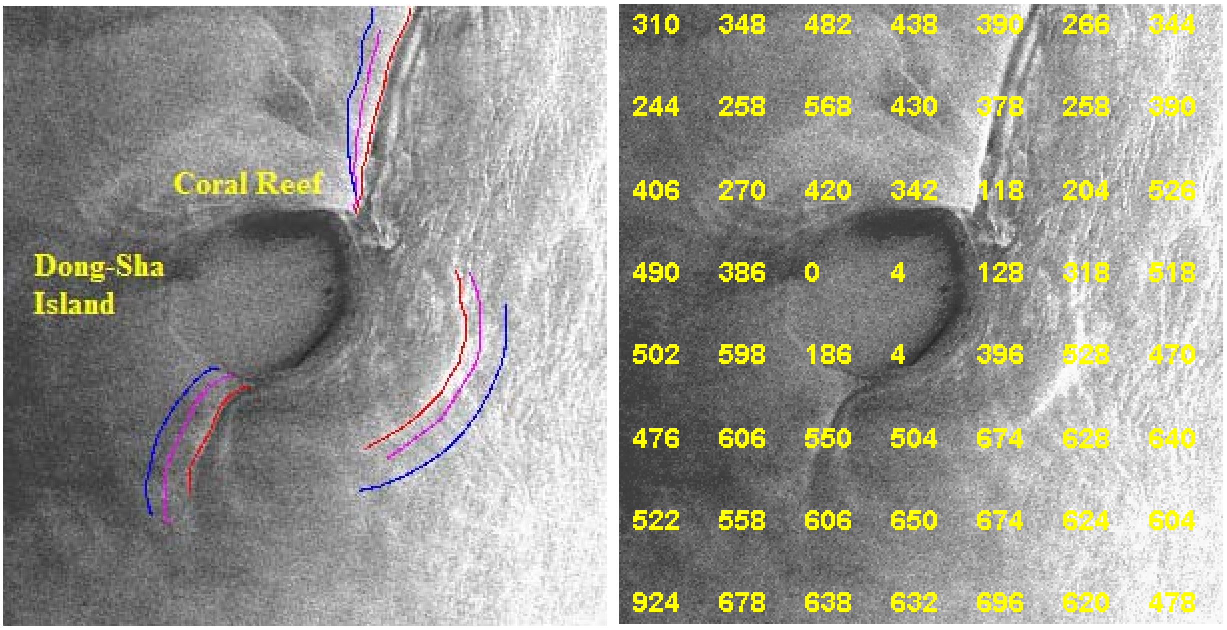

Figure 3. (Left panel) The ENVISAT SAR image on April 16, 2003, with the locations of the leading internal solitons digitized from ENVISAT, ERS-2, and MODIS image shown as red, magenta, and blue curves, respectively; (Right panel) The ENVISAT images on April 16, 2003 with the water depths in some locations shown in yellow.

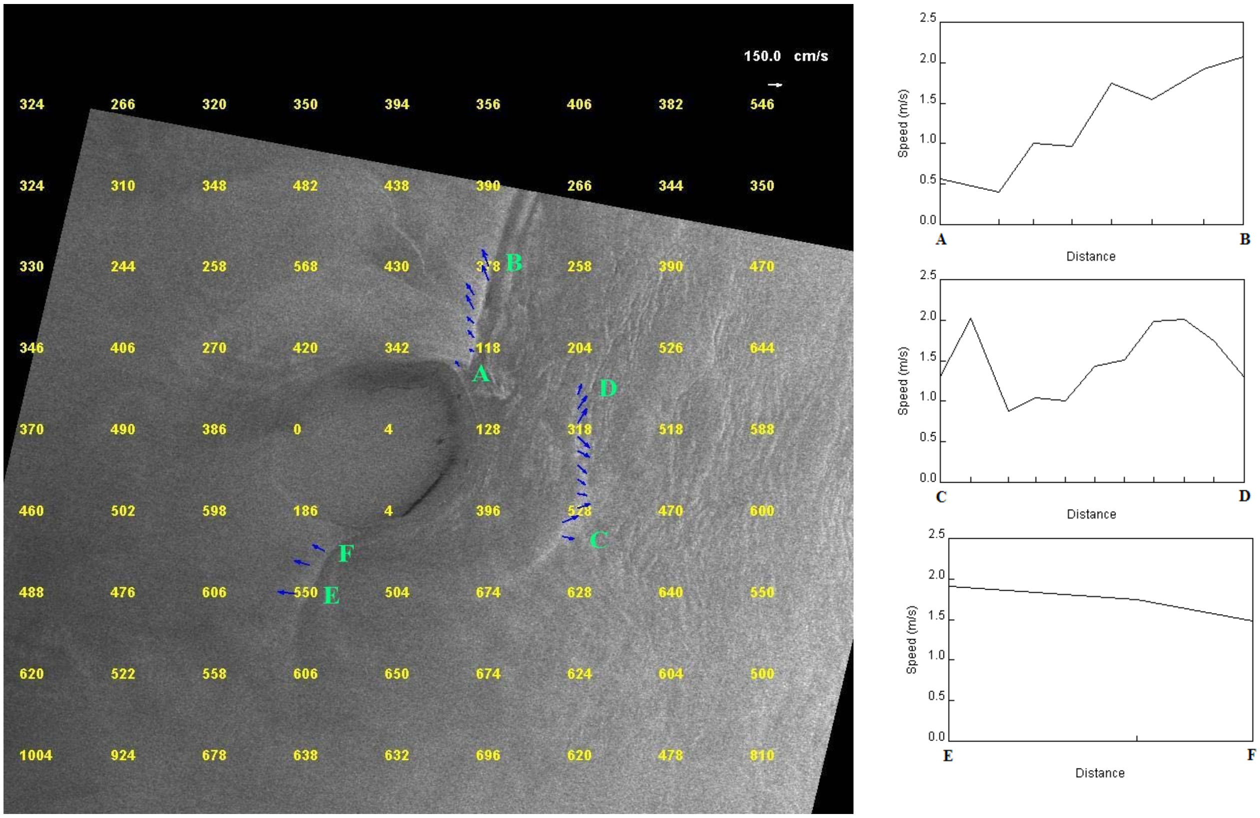

Figure 4. (Left Panel) The ENVISAT SAR image on April 16, 2003, overlaid with the internal wave propagation vectors (blue) derived from the image and the ERS-2 image collected 28 minutes later on the same day. The numbers in yellow is the water depths. (Right Panel) The lengths of the propagation vectors are shown in the three plots corresponding to the three internal wave sections AB, CD, and EF.

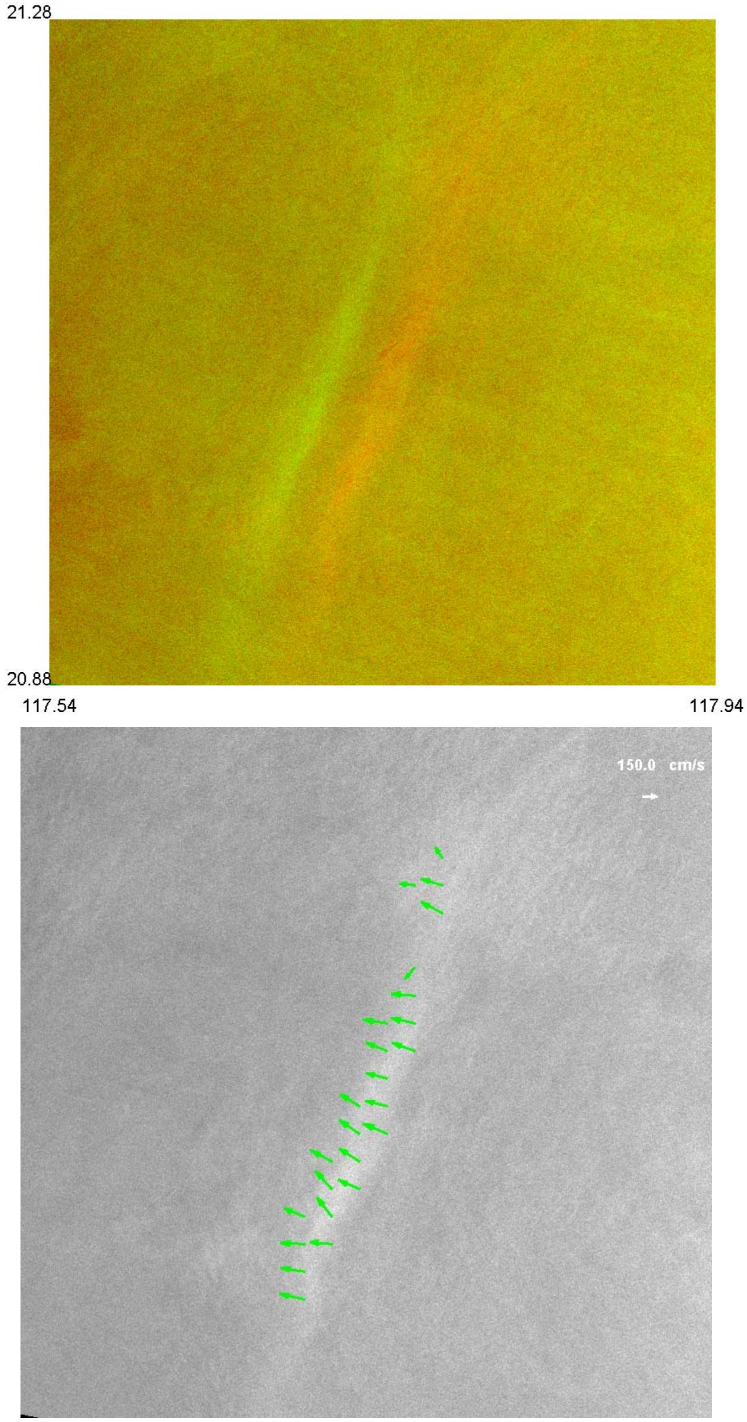

Figure 5. (Upper panel) The overlay of ENVISAT (red component) and ERS-2 (green component) SAR images on May 6, 2005 showing the internal wave position and signature differences in 28 minutes; (Lower panel) The internal wave propagation vectors derived from the two SAR images by the wavelet transform based internal wave tracking method.

IMPACT/APPLICATIONS

It is clear that these internal wave observations in the South China Seas provide a unique resource for addressing a wide range of processes (Liang et al., 1995; Liu et al., 1996, 1998; Hsu and Liu, 2000). These processes are listed as follows: the generation of elevation internal waves by upwelling, the evolution of nonlinear depression waves through the critical depth, the disintegration of solitons into internal wave packets, internal wave breaking induced by solitons, the generation of mode-two internal waves, and internal wave-wave interaction. The inclusion of these physical processes is essential to improve quantitative understanding of the coastal dynamics.

RELATED PROJECTS

None

REFERENCES

Hsu, M. K., A. K. Liu and C. Liu, 2000: A study of internal waves in the China Seas and Yellow Sea using SAR. Continental Shelf Res., 20, 389-410.

Hsu, M. K., and A. K. Liu, 2000: Nonlinear internal waves in the South China Sea, Canadian J. Rem. Sens., 26, 72-81.

Liang, N. K., A. K. Liu, and C. Y. Peng, 1995: A preliminary study of SAR imagery on Taiwan coastal water. Acta Oceanogr. Taiwanica., 34, 17-28.

Liu, A. K., J. R. Apel, and J. R. Holbrook, 1985: Nonlinear internal wave evolution in the Sulu Sea. J. Phys. Oceanogr. 15, 1613-1624

Liu, A. K., 1988: Analysis of nonlinear internal waves in the New York Bight. J. Geophys. Res. 93, 12317-12329.

Liu, A. K., C. Y. Peng, and Y.-S. Chang, 1996: Mystery Ship Detected in SAR Image, EOS, Transactions, American Geophysical Union, 77, No. 3, 17-18.

Liu, A. K., Y. S. Chang, M. K. Hsu and N. K. Liang, 1998: Evolution of nonlinear internal waves in the East and South China Seas. J. Geophys. Res. 103, 7995-8008.

Liu, A. K., S. Y. Wu, W. Y. Tseng, and W. G. Pichel, 2000: Wavelet analysis of SAR images for coastal monitoring, Canadian J. Rem. Sens., 26, 494-500.

Liu, A. K., Y. Zhao, and M. K. Hsu, 2006: Ocean surface drift revealed by synthetic aperture radar images, *Eos, Trans., AGU,* 87, No. 24, 233 & 239. [published, refereed]

PUBLICATIONS

Hsu, M. K., A. K. Liu, Y. Zhao, and K. Hotta, Satellite Remote Sensing of Spratly Islands Using SAR, 2007. [refereed]

Yu, J., Y. Yang, A. K. Liu, and Y. Zhao, Dynamics of Wave and Ice Interaction in the MIZ of Bering Sea, 2007 [refereed]

Zhao, Y., and A. K. Liu, Arctic Sea-Ice Motion and Its Relation to Pressure Field, *Journal of Oceanography*, Vol. 63, No. 3, pp. 505-515, 2007. [published, refereed]

Zhao, Y., A. K. Liu, and M. K. Hsu, Wave refraction observed from sequential satellite images, 2007. [refereed]

Zhao, Y., A. K. Liu, and M. K. Hsu, Deriving ocean surface drift using multiple SAR sensors, 2007. [refereed]

Zwally, H. J., D. Yi, R. Kwok, and Y. Zhao, ICESat Measurements of Sea-Ice Freeboard and Estimates of Sea-Ice Thickness in the Weddell Sea, 2007. [refereed]